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PREDICTION OF SEA SURVIVAL TIME

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ABSTRACT

Despite advances in personal protective equipment and locator technologies, circumstances can lead to life-threatening exposures at sea. Of particular concern is the survival time (ST) when a human is immersed in cold water. Estimation of ST is difficult since reliable controlled data are not available. However, studies on accidental immersion are sufficient to begin the construction and calibration of a predictive ST model. The model is based on the cylindrical core-shell concept of heat conduction with internal heat production augmented by shivering. Variables include ambient temperature, clothing protection (with and without leakage), subject characteristics, sea state, and level of immersion. If heat loss exceeds one's maximal rate of heat production, then ST is largely determined by the body's rate of cooling. Conversely, if a heat balance can be established, then ST is dependent on the depletion time of one's energy capacity based on glycogen stores. ST is defined by the deep core temperature reaching 30°C. As an example, the predicted ST for a healthy normal sedentary individual immersed in a heavy sea condition at 5°C are 1.9, 2.3, 4.8, 12.6, and 24.2 h for nude, shirt + sweater, shirt + anti-exposure suit, shirt + dry immersion suit, and 4 mm neoprene wet suit conditions, respectively. While the model predictions must be considered speculative, it can potentially serve as a valuable resource and decision aid. At present, it would be prudent to apply the predictions in a relative *vs* absolute sense; i.e., for comparative purposes.

EXECUTIVE SUMMARY

Following the submission of a previous report (Tikuisis and Frim 1994) on the prediction of survival time (ST) for cold air exposure, a requirement for a similar decision aid for cold water immersion was identified. Despite advances in personal protective equipment, circumstances can lead to life-threatening exposures at sea. Rescuers are often faced with a compromising decision; that is, whether to proceed immediately at some risk or to wait out a more favourable condition with less risk. Such a decision is more easily made if the condition of the casualities is known. Without direct contact, a prediction of survival status and outcome is required. Considering that reliable controlled data are unavailable for guidance, a computer-based predictive model offers the best potential for meeting this requirement.

A prediction is specifically required for individuals of varying physical characteristics wearing various types and layers of clothing. Further, it would be desirable to program the effect of poor health and/or injury. Development of the model began with an extension of the earlier version to two separate cylinders to accommodate partial immersion conditions. This was followed by considering the insulative protection of various clothing ensembles with and without water leakage. Finally, injury was factored in according to blood loss or type of trauma; however, considering that very little is known about the impact of injury on human thermoregulation, this aspect is the most speculative feature of the model.

The PC version of the model (described in the APPENDIX) allows the user to define the inputs or to select them from a menu. Nor surprisingly, ST is predicted to decrease with i) decreased body fatness, ii) decreased clothing protection, iii) increased wetness, iv) decreased metabolic capacity, and v) injury. As an example, the predicted ST for a healthy normal sedentary individual immersed in a heavy sea condition at 5°C are 1.9, 2.3, 4.8, 12.6, and 24.2 h for nude, shirt + sweater, shirt + anti-exposure suit, shirt + dry immersion suit, and 4 mm neoprene wet suit conditions, respectively.

As previously expressed (Tikuisis and Frim 1994), a prediction on survival outcome is speculative since reliable data are not available. This caveat and its consequences are further punctuated with the addition of new variables in the present model. Greater confidence can be placed on a prediction involving conditions close to those reported on accidental immersions that were used to calibrate the original model. Departure from these conditions entails greater uncertainty and as previously recommended, a prediction may be more meaningful if applied in a relative *vs* absolute sense; i.e., for comparative purposes.

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INTRODUCTION

Advances in personal protective equipment and locator technologies have greatly aided casualities of shipwrecks, air crashes, and vehicular accidents. Yet, circumstances exacerbated by inadequate preparation can quickly lead to life-threatening exposures. We are especially reminded of this during harsh conditions at sea where immersion multiplies the heat loss rate compared to that of an equivalent air temperature exposure. When confronted with such a situation, rescuers are often faced with a compromising decision; that is, whether to proceed immediately at some risk or to wait out a more favourable condition with less risk. Such a decision is more easily made if the condition of the casualities is known, usually through direct communication. However, failing this possibility, a prediction of survival status and outcome is required. Years of experience hones the professional's predictive capability, yet, with many confounding variables, each rescue operation presents a unique challenge. A computer-based predictive model can potentially offer a valuable resource and decison aid. It is also noteworthy that search and rescue operations are extremely expensive and are often continued for much longer than is necessary primarily on humanitarian grounds but also because guidelines for continuation are virtually non-existent.

Predictions on survival outcome are speculative since reliable data are not available. This caveat and its consequences have been discussed in a previous report (Tikuisis and Frim 1994) that outlined the development of a mathematical model for the prediction of survival time for cold air exposure. The model was derived using known biophysical and physiological characteristics, and calibrated with known survival cases, yet its predictive capability largely remains untested. As in most model developments of this nature, validation and refinement are ongoing processes subject to the availability of new information. The present requirement for the prediction of sea survival must be similarily approached.

The basic model construct adopted herein is outlined in Tikuisis and Frim (1994). The goals of the present modelling effort are to incorporate the following variables for the prediction of sea survival: partial immersion, various types of clothing protection, wetness, and the effect of injury. As in the previous model, the individual is assumed to be sedentary and therefore reliant on shivering as the only source of heat production beyond normal resting values. Since the focus is on survival, cold-induced injuries and extremity cooling are not considered. End of survival or survival time (ST) is predicted when the body's deep core temperature reaches 30°C. Although the individual is unlikely to die from hypothermia at this point, he or she will be dysfunctional and death is imminent unless outside intervention can

reverse further cooling. Aside from taking basic anthropometric measures such as mass, height, and body fatness into account, no distinction is presently made for gender differences in exposure survivability.

MODEL DEVELOPMENT

1. Configuration

The model assumes steady state heat conduction in a cylindrical core-shell configuration. Heat is generated uniformly within the core region and its central axis represents the deep body core temperature. The two annular concentric shells represent the fat plus skin and the clothing plus still boundary layer, respectively. A schematic of the model and its relevant heat transfer equations are outlined in Tikuisis (1995).

To accommodate partial immersion, the present model consists of two cylinders aligned end-to-end. The convention adopted herein is to air-expose the upper cylinder (#1) and water-immerse the lower cylinder (#2). However, either total air exposure or water immersion can be simulated by adjusting the appropriate cylinder fractions to zero or unity. Each cylinder (i = 1,2) will usually have a different rate of heat loss and consequently undergo a different change in mean temperature; i.e.,

(1) $$\Delta T_{b_i} = \frac{(M - Q_i) \cdot \Delta t}{cb}$$

where T_b is the mean cylinder temperature, M is the metabolic rate, Δt is the time step, cb is the heat capacity, and Q is the rate of heat loss given by

(2) $$Q_i = \frac{(T_0 - T_{3_i})}{R_{eff_i}}$$

where T_0 and T_3 are the central core and ambient temperatures, respectively, and R_{eff} is the effective thermal resistance (Tikuisis 1995). The overall change in mean body temperature (comprising both cylinders) is given by

(3) $$\Delta T_b = (1 - b) \cdot \Delta T_{b_1} + b \cdot \Delta T_{b_2}$$

where b represents the overall fraction of body immersion. The central core temperature of each cylinder is given by (Tikuisis 1995)

(4) $$T_{0_i} = \frac{a_{2i} \cdot T_{3_i} + \left(\frac{r_{3_i}}{r_2}\right) \cdot \left[2 \cdot T_{b_i} \cdot R_{eff_i} - (2 - f_{co}) \cdot T_{3_i} \cdot \left(R_{eff_i} - a_{3i}\right)\right]}{a_{2i} + \left(\frac{r_{3_i}}{r_2}\right) \cdot \left[f_{co} \cdot R_{eff_i} + (2 - f_{co}) \cdot a_{3i}\right]}$$

where

(5) $$a_{2i} = \frac{r_{3_i}}{k_{sf}} \cdot \ln\left(\frac{r_2}{r_1}\right)$$

(6) $$a_{3i} = \frac{r_{3_i}}{k_{cl_i}} \cdot \ln\left(\frac{r_{3_i}}{r_2}\right)$$

and where r is radius, fco is the fraction by volume of the core region, and k_{sf} and k_{cl} are the thermal conductivities of the skin plus fat compartment and the clothing plus still boundary layer, respectively. Note that r_1 and r_2 represent the cylindrical radii to the outer core boundary and skin surface, respectively, which are common to both cylinders whereas r_3 represents the radius to the outer surface of the still boundary layer which varies with the ambient condition (i.e., air *vs* water), as does the external thermal conductivity, k_{cl}.

Assuming that the cylinders are sufficiently well-stirred in the deep core so that their temperatures are the same, its value is found by equating T_{0_1} to T_{0_2} with the result that

(7) $$T_{b_1} = \frac{T_b - \frac{b}{2 \cdot R_{eff_2}} \cdot \left\{c_{22} + \frac{(c_{32} / c_{31}) \cdot (c_{11} - ra_1 \cdot c_{21}) - c_{12}}{ra_2}\right\}}{(1 - b) + b \cdot \left(\frac{c_{32}}{c_{31}}\right) \cdot \left(\frac{ra_1}{ra_2}\right) \cdot \left(\frac{R_{eff_1}}{R_{eff_2}}\right)}$$

and

(8) $$T_{b_2} = \frac{1}{2 \cdot R_{eff_2}} \cdot \left\{c_{22} + \frac{(c_{32} / c_{31}) \cdot \left[c_{11} + ra_1 \cdot \left(2 \cdot T_{b_1} \cdot R_{eff_1} - c_{21}\right)\right] - c_{12}}{ra_2}\right\}$$

where T_b is the overall mean body temperature which changes according to Eq. 3 and

(9) $$c_{1i} = a_{2i} \cdot T_{3_i}$$

(10) $c_{2i} = (2 - f_{co}) \cdot \left(R_{eff_i} - a_{3i}\right) \cdot T_{3_i}$

(11) $c_{3i} = a_{2i} + ra_i \cdot \left[f_{co} \cdot R_{eff_i} + (2 - f_{co}) \cdot a_{3i}\right]$

(12) $ra_i = r_{3_i} / r_2$

Note that T_0 is obtained by substituting the appropriate value of T_{b_i} (Eq. 7 or 8) into Eq. 4. The numerical procedure used to calculate T_0 over time is outlined in Tikuisis (1995).

2. Clothing

Clothing adds a protective layer of insulation to the body's surface. Its value is usually stated in units of clo which the model is designed to accept [1 clo of insulation provides thermal comfort for a sedentary individual in air at 22-24°C (Fanger 1970)]. If wet, clothing will lose much of its insulative property. For most of the clothing ensembles considered in this study, immersion insulation values have been determined with a mannikin for stirred and turbulent water conditions, hereafter referred to as light and heavy seas; values are estimated for the other ensembles (see Table 1). For the separate garment items considered in this study, the intrinsic dry insulation value is converted to immersion conditions depending on the degree of wetness (defined below). In the case of the wet suit, immersion values were estimated from the experimental results reported by Steinman et al. (1987).

The intrinsic dry insulation values (I_{cl}) exclude the external air boundary layer following the guidelines recommended by McCullough (1985). The total dry insulation of a combination of individual garments such as a shirt + sweater is obtained from the following summation formula (McCullough 1985)

(13) $\text{ensemble } I_{cl} = 0.676 \cdot \sum I_{cl} + 0.117$

plus the external air layer insulation determined with the algorithm developed by Danielsson (1993). Dry values are used for non-immersion, but subject to wind and wetness corrections. In cases where only the immersed insulation value is known, estimations are made of the garments non-immersed value using comparative values from the measured ensembles and the algorithm developed by Danielsson (1993).

Table 1: List of insulation options [in clo units; "*" values were supplied by M.E.T.A. Research Inc. (Wendell Uglene; private communication), "**" from Allan et al. (1982), "†" values from Capt(N) C.J. Brooks, "*†" values from Wolff et al. (1985), others were estimated]. The dry insulation values exclude the external air layer whereas the wet values include the external still water boundary layer. Where manikin-determined values for water immersion are not given (-), the human-use value is assumed equal to 0.07 x dry value + (0.05 if a light sea or 0.01 if a heavy sea condition). Where manikin-determined values are given, the human-use values are assumed to be 10 and 40% higher for light and heavy sea conditions, respectively (Romet et al. 1991). Where manikin-determined values are given for only the light or heavy sea condition, the other is estimated assuming a 5:2 ratio based on the average observed difference. "ug" and "fs" refer to undergarment and flying suit, respectively.

		Light Sea		Heavy Sea	
Exposure Description	**Dry**	**Manikin**	**Human**	**Manikin**	**Human**
Single Garments					
nude	0	-	0.05	-	0.01
t-shirt (1)	0.10	-	0.06	-	0.02
long-sleeved shirt (2)	0.33	-	0.07	-	0.03
heavy sweater (3)	0.40	-	0.08	-	0.04
vest (4)	0.20	-	0.07	-	0.03
work jacket (5)	0.51	-	0.09	-	0.05
Ensemble					
parka + 1 + 2 + 3	1.8*	0.16*	0.18	0.07*	0.10
anti-exposure worksuit + 2	2.0*	0.42*	0.46	0.17*	0.24
survival coverall + 2	2.0	0.50*	0.55	0.20*	0.28
fisherman's worksuit + 2 + 3	2.2	0.50	0.55	0.20*	0.28
snowmobile suit + 2	2.0	0.38*	0.42	0.15	0.21
aviation coverall + cotton-ribbed ug + 4	1.7**	0.27**	0.30	0.11	0.15
aviation coverall + single pile + 4	2.0**	0.51**	0.56	0.20	0.29
aviation coverall + double pile + 4	2.3**	0.77**	0.85	0.31	0.43
quick-don suit + 1 + 2 + 3	2.2	0.62*	0.68	0.25	0.35
quick-don suit + double pile + fs	2.9**	0.79**	0.87	0.32	0.44
dry immersion suit + 2 + 4 + 5	2.0†	0.51†	0.56	0.20	0.28
dry immersion suit + single pile + 4	2.1†	0.81†	0.89	0.32	0.45
dry immersion suit + double pile + 4	2.4†	1.01†	1.11	0.40	0.57
Wet Suit					
4 mm neoprene	0.77*†	-	0.28	-	0.16
7 mm neoprene	1.18*†	-	0.40	-	0.25

3. Wetness/Leakage

Wetness reduces the insulation of clothing by displacing trapped air with water which has a much higher heat conductivity. This reduction has been characterized differently depending on whether the individual is primarily air-exposed (wetness through pre-immersion or precipitation) or water-immersed (*via* leakage). If water-immersed, the reduction due to leakage is approximated by

(14) $$loss\ of\ insulation\ (\%) = 100 \cdot \left(1 - e^{-0.022 \cdot \sqrt{wetness}}\right)$$

based on the fit of data on immersion-protection clothing presented by Allan et al. (1985) and where *wetness* is the water ingress in gm•m^{-2}. The maximum reduction is limited to the value of the still water insulation pertaining to the thickness of the garment using a thermal conductivity ratio of 0.07:1 between water and air (Tikuisis and Frim 1994). The immersion values given in Table 1 assume complete wetness for all garments and ensembles except for the quick-don and immersion suits (last 5 entries). In the latter cases, the suits are assumed dry; however, if wet, then Eq. 14 is applicable to the immersed values listed in Table 1.

If air-exposed, the reduction is linearly approximated by

(15) $$loss\ of\ insulation\ (\%) = \begin{cases} 0.0554 \cdot wetness & if\ wetness \le 316.2\ gm \cdot m^{-2} \\ 9.17 + 0.0264 \cdot wetness & if\ wetness \ge 316.2\ gm \cdot m^{-2} \end{cases}$$

based on the fit of data presented by Boutelier (1979). Wetness during air exposure introduces an evaporative component to body heat loss, expressed as (Nishi 1981)

(16) $$Ev = f_w \cdot E_{\max}$$

where fw is the fraction of maximum skin wetness assumed to be linearly related to the above insulation reduction factor and $E_{\max}$ is the maximum evaporative heat loss (in W•m^{-2}) given by

(17) $$E_{\max} = \frac{16.5 \cdot h_{air} \cdot (P_s - P_a)}{1 + 0.92 \cdot h_{air} \cdot R_{cl}}$$

and where h_{air} is the external heat transfer coefficient ($W \bullet m^{-2} \bullet K^{-1}$), R_{cl} is the internal clothing insulation including air layers ($m^2 \bullet K \bullet W^{-1}$), and P is the vapour pressure (kPa)

(18) $$P_s = P_{sat(T_s)}$$

(19) $$P_a = \frac{RH}{100} \cdot P_{sat(T_a)}$$

(20) $$P_{sat(T_x)} = \exp\left(16.6536 - \frac{4030.183}{T_x + 235}\right)$$

and where RH is the relative humidity (%), P_{sat} is the saturated vapour pressure, T is temperature, and the subscript x refers to either s or a denoting the skin surface (i.e., at r_2) or ambient values, respectively.

It is assumed from an *a priori* calibration that shivering increases in response to Ev through a non-linear dependence on the shivering intensity, M_{shiv} . However, this increase is limited so that the cooling effect of evaporative heat loss does not lead to increases in metabolism when body temperature is relatively high. The following *ad hoc* approximation is therefore applied

(21) $$\textit{increase in } M_{shiv} = Ev \cdot \left[1 - \exp\left(-\frac{M_{shiv}}{M_{shiv\max}}\right)\right]$$

where M_{shiv} in the exponent refers to the predicted shivering metabolic rate based solely on body temperatures and $M_{shiv\max}$ is the maximum shivering intensity.

4. Injury

There is very little information on the effect of injury on shivering thermogenesis. The following is a mathematical construct based on a general interpretation of the pathophysiology of injury. This construct is highly speculative and subject to modification as better information becomes available. It is simply assumed that the maximum shivering intensity decreases non-linearly with increased severity of injury. Two aspects of injury, blood loss and trauma, are considered separately. The model accepts the higher severity of the two as the determinant of maximum shivering inhibition.

A blood loss of up to 15% can be tolerated without any deleterious effects while shock is likely at 40% of blood loss (Bowen et al. 1988). The model assumes a linear decrease in the maximum shivering intensity from 0 to 100% as blood loss increases from 15 to 40% of total volume.

Incorporation of trauma is modelled after the injury severity score (*iss*) introduced by Baker et al. (1974). The *iss* takes into account up to three of the most serious types of injuries which include lacerations, contusions, abrasions, avulsions, burns, fractures, etc., in general or to specific parts of the body. Each injury type is assigned an AIS (abbreviated injury scale) grade (from 0 to 5; CMAAS 1971) and the *iss* is the sum of their squares. According to Little and Stoner (1981), *iss* values of 1-5, 6-12, and > 12 represent minor, moderate, and severe trauma, respectively. The present model assumes the following *ad hoc* sigmoidal decrease in maximum shivering intensity as *iss* increases beyond a value of 6, otherwise no change occurs:

(23) $$\textit{decrease in } M_{shiv\,\max} = \operatorname{sech}\left(\frac{iss-6}{4.55}\right)$$

which leads to reductions of 50 and 90% for *iss* = 12 and 20, respectively.

RESULTS

A number of examples will be given to illustrate the predictive range of the model, although it is must be emphasized that the predictions are untested and that it is impractical to demonstrate all variants. The model has been implemented on a PC which should satisfy most user requirements. This version (outlined in the APPENDIX) is limited to predictions of ST (i.e., when the deep core temperature reaches 30°C) whereas the original version can be used to predict the course of body temperatures, heat production, and heat loss.

A base set of conditions is adopted as a starting point and variations on this set are then explored. The base set is defined as follows:

- complete immersion in 5°C water
- average individual (73.9 kg, 1.77 m, 17.7% body fatness)
- full metabolic capacity and no injury

The metabolic capacity addresses the ability of the individual to sustain shivering (Tikuisis 1995). If nutritionally deprived and/or fatigued, it can be expected that the individual's

metabolic capacity falls below normal levels. In the present model, the metabolic capacity is expressed as a percentage of its normal value.

1. Insulative Options

Table 2 lists the predicted ST for the base set of conditions with the shirt + sweater combination and for all the ensemble options listed in Table 1. The marked decreases in predicted ST from light to heavy sea conditions highlights the adverse effect of increased turbulence. Figure 1 below illustrates the relationship between the insulation value during immersion and the predicted ST for the light sea condition.

Table 2: Predicted survival times for complete immersion ($b = 1$) of an average individual in light and heavy sea conditions at 5°C. The immersed insulation values for the shirt + sweater ensemble are 0.09 and 0.05 clo, respectively. The other insulation values are listed in Table 1 and include the still water boundary layer. The numerical references 1-5 respectively refer to the t-shirt, shirt, sweater, vest, and work jacket listed in Table 1.

	ST (h)	
Exposure Description	**Light Sea**	**Heavy Sea**
nude	2.3	1.9
shirt + sweater (2 + 3)	2.7	2.3
parka + 1 + 2 + 3	3.8	2.8
anti-exposure worksuit + 2	10.1	4.8
survival coverall + 2	13.4	5.5
fisherman's worksuit + 2 + 3	13.4	5.5
snowmobile suit + 2	8.9	4.3
aviation coverall + cotton-ribbed ug + 4	5.9	3.4
aviation coverall + single pile + 4	13.8	5.7
aviation coverall + double pile + 4	29.3	9.2
quick-don (dry) suit + 1 + 2 + 3	19.3	7.0
quick-don (dry) suit + double pile + fs	30.7	9.5
dry immersion suit + 2 + 4 + 5	13.8	5.5
dry immersion suit + single pile + 4	32.1	9.8
dry immersion suit + double pile + 4	> 36	14.2
4 mm neoprene wet suit	5.5	3.5
7 mm neoprene wet suit	8.3	4.9

2. Individual Attributes

This section considers the impact of body fatness, partial immersion, wetness, and injury on the prediction of survival time. Figure 1 shows the predicted ST for three body types (CFLRI 1988) immersed up to the neck in a 5°C light sea condition under varying insulation values.

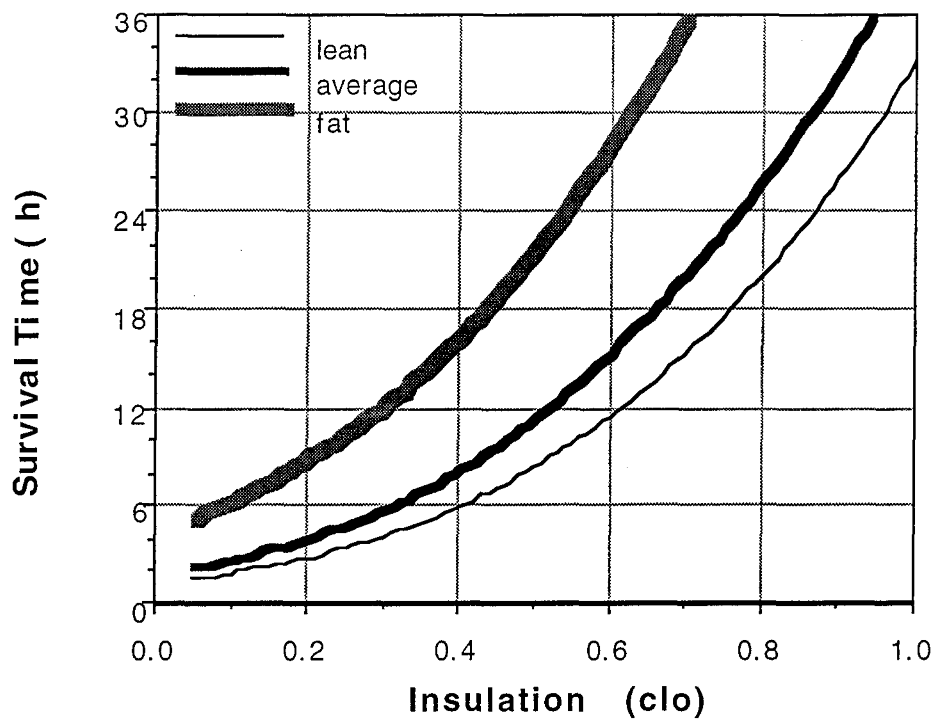

Figure 1: Predicted survival time plotted against the 'immersed' or *in situ* insulation value for lean (66.3 kg, 1.77 m, 11.2% body fat), average (73.9 kg, 1.77 m, 17.7% body fat), and fat (88.2 kg, 1.77 m, 28.6% body fat) individuals in a 5°C light sea condition. The lowest insulation value (0.05 clo) pertains to a nude condition whereas the highest value (1.0 clo) approximates the highest dry immersion suit condition (see Table 1).

Figure 1 clearly illustrates the advantage of increased body fatness in terms of extended ST where values increase by more than a factor of 2 for fat *vs* lean individuals. This difference may partly explain the relatively wide range of reported survival times in accidental immersions (Molnar 1946; Veghte 1972).

Table 3 lists the predicted ST for a variety of conditions, each involving an average individual wearing the quick-don ensemble (see Table 1) and immersed in a 5°C light sea

condition. Where partial immersion is considered, the upper portion of the model is air-exposed to 10°C under a low wind condition (2 km•h^{-1}) and 100% relative humidity. With complete immersion (b = 1), the predicted ST is 19.3 h, whereas it exceeds 36 h with chest-level immersion (b = 0.6).

Table 3: Predicted survival times for an average individual in a quick-don ensemble (+ t-shirt + long-sleeved shirt + heavy sweater) immersed under various conditions in a light sea at 5°C and air at 2 km•h^{-1} and temperature at 10°C. These include changes in immersion level, wetness, metabolic capacity, and injury (see text for details).

Immersion Level (*b*)	**Wetness (gm/m**2) Upper/Lower Body**	**Metabolic Capacity (%)**	**Blood Loss (%)/ Trauma (*iss*)**	**ST (h)**
neck (1.0)	- /0 (dry)	100	0/0	19.3
chest (0.6)	0/0	100	0/0	> 36
neck (1.0)	- /0	80 (high)	0/0	16.7
neck (1.0)	- /0	50 (moderate)	0/0	12.6
neck (1.0)	- /0	20 (depleted)	0/0	8.2
neck (1.0)	- /0	100	20 / 9.2 (low)	13.1
neck (1.0)	- /0	100	27.5/ 12 (moderate)	7.0
neck (1.0)	- /0	100	35 / 16.4 (severe)	4.3
neck (1.0)	- /100 (low)	100	0/0	13.6
neck (1.0)	- /1000 (moderate)	100	0/0	7.4
neck (1.0)	- /5000 (high)	100	0/0	3.9
none (0.0)	400 (low))/ -	100	0/0	> 36
none (0.0)	1550 (moderate)/ -	100	0/0	33.6
none (0.0)	2700 (high)/ -	100	0/0	9.5
thigh (0.2)	1550/1000	100	0/0	23.2
chest (0.6)	1550/1000	100	0/0	12.3

Three levels of metabolic capacity are considered, 80% (high), 50% (moderately depleted), and 20% (severely depleted). The respective predicted ST are 16.7, 12.6, and 8.2 h. With regard to trauma, values of 20% blood loss or *iss* = 9 (low), 27.5% blood loss or *iss* = 12 (moderate), and 35% blood loss or *iss* = 15 (severe) lead to predicted ST of 13.1, 7.0, and 4.3 h, respectively.

Three levels of wetness (low, moderate, and high representing 20, 50, and 80% of maximum wetness, respectively) are considered for the complete immersion and no immersion conditions. Begining with immersion, the respective predicted ST are 13.6, 7.4, and 3.9 h. For air exposure only, but with wetness at the same relative but different absolute levels, predicted ST are > 36, 33.6, and 9.5 h, respectively.

Finally, example predictions are made for 50% wetness under partial immersion conditions (b = 0.2 and 0.6 representing thigh and chest levels). In these cases, the predicted ST are 23.2 and 12.3 h, respectively.

DISCUSSION

First and foremost, it cannot be overly emphasized that the model predictions are highly speculative. This is a natural consequence of the model's development and it cannot be diminished without appropriate testing. Such testing can be of a peripheral or supportive nature ranging from measurements of maximal shivering rates under metabolically-challenged conditions to a greater resolution of clothing insulation under varying sea states. Other testing can be more direct involving comparisons between predictions and accidental events. However, without detailed documentation, the latter's value is limited.

Certain predictions may appear high, especially for very cold water and low levels of protection. The model does <u>not</u> take into account respiratory distress from sudden immersion nor the possibility of drowning, and the individual is assumed to have flotation. The ST prediction is strictly based on body cooling and the estimates given are consistent with those reported for accidental immersions at sea (Molnar 1946; Veghte 1972).

Although model predictions are stated as absolute endpoints, their value may be better appreciated in relative terms. For example, predictions on extending ST with added clothing protection can be compared against the benefit of increased water impermeability of a single garment. As mentioned earlier, the number of possible combinations and variations infinitely exceed the few examples examined in this study. It, therefore, would not be surprising to find ST predictions that are contrary to specific cases, particularly those that diverge from the conditions examined herein. Greater certainty can be ascribed to those conditions that more closely resemble whole-body immersions involving completely wet clothing since this is representative of the reported sea survival cases that were used to calibrate the original model. Until our knowledge of human thermoregulatory response to cold exposure under various

degrees of clothing protection and health status is improved, predictions of ST will remain speculative with continued reliance on extrapolative techniques.

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APPENDIX: PC APPLICATION

The PC version of the sea survival time (SEA) model using MS WINDOWS® is designed for expert and non-expert use. It is necessary to have WINDOWS installed and running on the computer. Insert the Sea Survival ST floppy disk into an appropriate drive, select this drive from the 'File Manager' in WINDOWS, and proceed to setup. The setup program can be executed by either double clicking on the 'SETUP.EXE' file or by typing SETUP under the 'Run' option within the 'File' menu. The user will be prompted for a destination directory where the necessary files will be expanded and stored on the computer. SEA can be run directly from the 'Program Manager' by adding it as a 'New Item' to any 'Program Group'. Program execution is initiated by depressing 'RUN'.

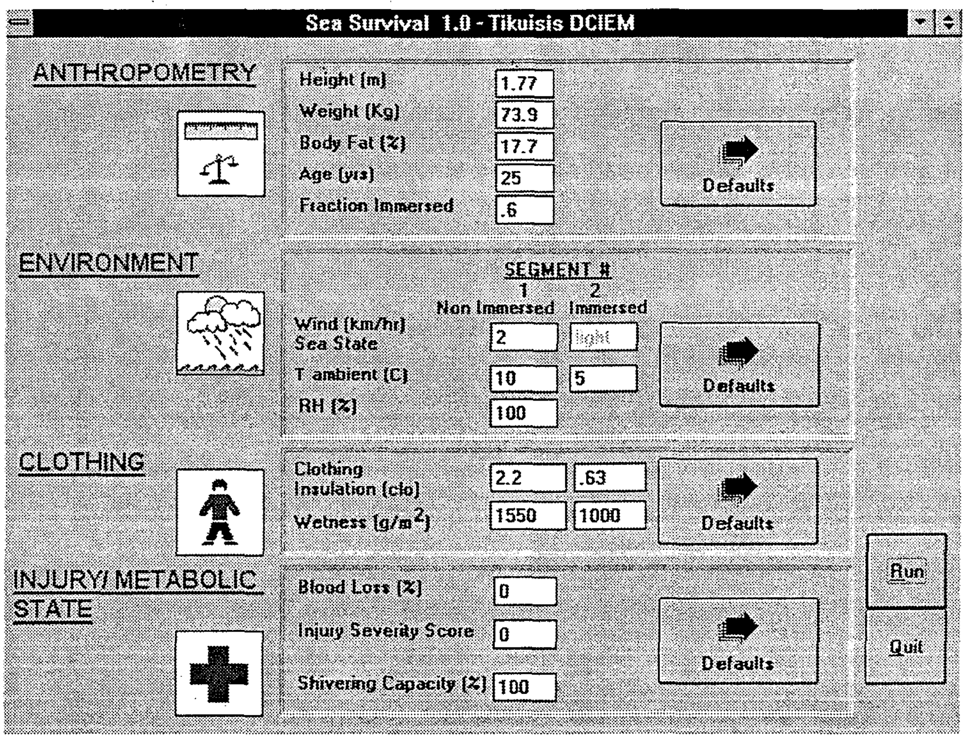

Figure A1: Main input screen; values shown pertain to the last entry in Table 3.

The user must define or select from a default menu the subject anthropometric, environmental, clothing, metabolic capacity, and injury inputs. Inputs can be mixed between user-defined and default values, and they can be changed after each run using the 'Edit' option in the output box. Figure A1 shows the main input screen with values corresponding to the example of an average individual in a quick-don ensemble at chest-level immersion and moderate level of wetness (last entry in Table 3). The default screens are self-explanatory; the

example shown in Fig. A2 illustrates the clothing options. The output is a singular prediction of ST stated as the "Estimated Survival Time to Critical Hypothermia" corresponding to a deep core temperature of 30°C and it appears in a separate box superimposed on the main input screen after 'RUN' is depressed.

SEA will not execute unless all inputs are specified. User-defined values are checked for physical and physiological validity, and the user is prompted if a correction is necessary. Defaults are sufficiently wide-ranging to cover most situations. For example, anthropometric options include lean, average, and fat individuals. If a default is selected, its numeric value is indicated on the input screen, and if inappropriate, the user can override the selection. One exception to this freedom of input choices occurs when certain clothing combinations are selected for immersion. In these cases (ensembles that become completely wet when immersed), the immersed *clo* value is fixed and the letters 'NA' will appear in the 'Wetness' box. Another exception pertains to the sea state where the user must select either 'light' or 'heavy' from the Clothing default list.

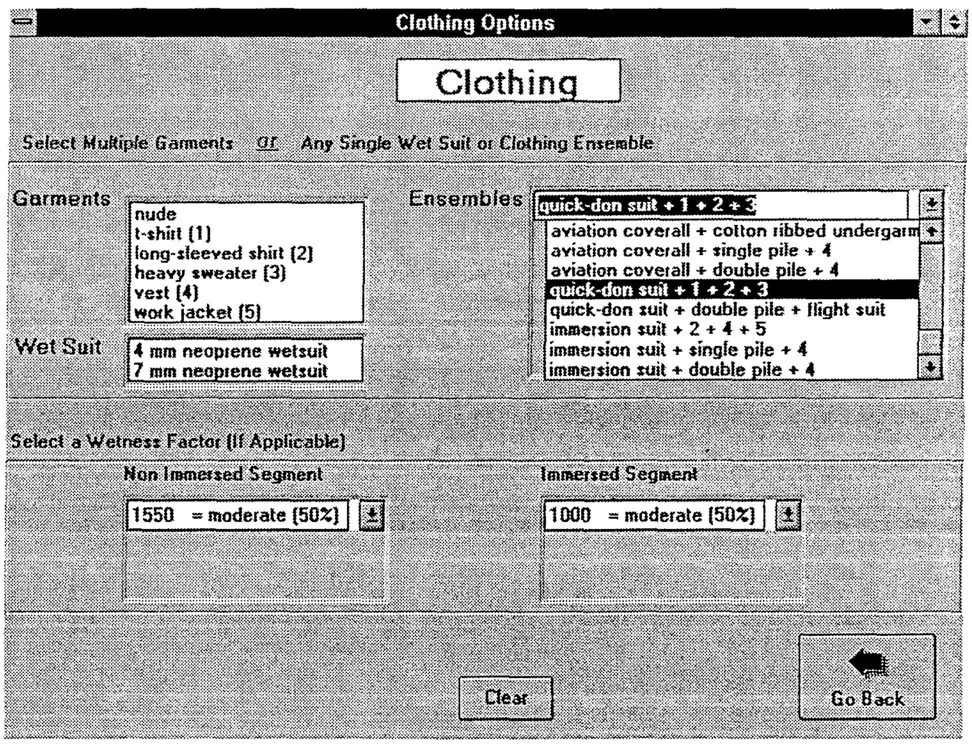

Figure A2: Clothing options default screen. Ensemble options are selected from a "pull-down" menu as are the wetness factors for both segments.

The user should be aware that the insulative input values (in clo units) pertain to the dry intrinsic insulation without the 'Environment' or 'Wetness' taken into account, unless the clothing chosen is a wet suit or a water-permeable ensemble in which case the immersed input value reflects the *in situ* wetted state. Wetness inputs are restricted to units of $gm \bullet m^{-2}$; however, the user has the option of choosing low, moderate, or high degrees of wetness from the default list (the non-linearity between wetness in $gm \bullet m^{-2}$ and in % precludes the use of wetness % values beyond the default options).

To ensure a problem-free execution, all inputs should be completed from the top down. It is necessary to enter the fraction of body immersion (b) before the environmental and clothing options are assigned. By convention, segment #1 represents the non-immersed portion and segment #2 represents the immersed portion. Note that the model has been calibrated such that $b = 0.2$ and 0.6 represent thigh and chest level immersions. If b is changed after a run, the environmental and clothing inputs should be verified. If difficulties occur, restart the program.

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Despite advances in personal protective equipment and locator technologies, circumstances can lead to life-threatening exposures at sea. Of particular concern is the survival time (ST) when one is immersed in cold water. Estimations of ST are difficult since reliable controlled data are not available. However, studies on accidental immersions are sufficient to begin the construction and calibration of a predictive ST model. The model is based on the cylindrical core-shell concept of heat conduction with internal heat production augmented by shivering. Variables include ambient temperature, clothing protection (with and without leakage), subject characteristics, sea state, and level of immersion. If heat loss exceeds one's maximal rate of heat production, then ST is largely determined by the body's rate of cooling. Conversely, if a heat balance can be established, then ST is dependent on the depletion time of one's energy capacity based on glycogen stores. ST is defined by the deep core temperature reaching 30°C. As an example, the predicted ST for a healthy normal sedentary individual immersed in a heavy sea condition at 5°C are 1.9, 2.3, 4.8, 12.6, and 24.2 h for nude, shirt + sweater, shirt + anti-exposure suit, shirt + dry immersion suit, and 4 mm neoprene wet suit conditions, respectively. While the model predictions must be considered speculative, it can potentially serve as a valuable resource and decision aid. At present, it would be prudent to apply the predictions in a relative *vs* absolute sense; i.e., for comparative purposes.

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Survival Time, Hypothermia, Water Immersion, Protective Clothing, Modelling